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Optimization of Positional Angle of Propeller–Aspirator Pump Aerator and Its Performance Evaluation at Different Dynamic Condition

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Abstract. Aeration test was conducted in a brick masonry tank of dimension 5 × 3 × 1.5 m^3 to evaluate the optimum geometric condition of Propeller –aspirator pump aerator, i.e., positional angle of propeller shaft (α).The results indicated a maximum SAE at α = 75°. Keeping the geometric condition constant (α = 75°), aeration experiments were further conducted at different rotational speeds of propeller shaft, N ranging from 1420 to 2840 rpm with an interval of 355 rpm and different values of submergence depth, d from 140 to 460 mm with an interval of 80 mm to evaluate the effect of dynamic conditions on aeration characteristics. Non-dimensional numbers related to standard aeration efficiency (SAE) and wire power (P) termed as E and Ne respectively, were introduced. It was found that E and Ne could be well correlated with Froude number (Fr) and Reynolds number (Re) respectively.

Keywords: Aeration, Positional angle, Dimensionless numbers

1. Introduction

Dissolved oxygen (DO) is considered to be the most vital water quality parameter in water and wastewater treatment. Atmospheric oxygen gets dissolved in water through diffusion process. As diffusion is a very slow process, aerators are generally used to maintain desired level of DO in water body. The aerators consume around 60% of the total energy consumption in a typical activated sludge wastewater treatment plant [1]. Therefore, the prime idea is to minimize the energy consumption by utilizing properly designed aerators. Presently diffused-air and surface aerators are being popularly used in wastewater treatment plants as well as in lakes and aquacultural ponds.

The propeller-aspirator-pump aerator draws atmospheric air through a rotating hollow shaft which is connected to an electric motor at one end and a propeller at the other end which is submerged under water. Basically the propeller accelerates the water to a velocity high enough to cause a drop in pressure over the diffusing surface. This forces air to pass through a diffuser in the hollow shaft and enter into the water as fine bubbles. The fine bubbles thus formed are thoroughly mixed with the water due to the turbulence created by the propeller. The aeration performance of a propeller-aspirator-pump aerator depends on the positional angle of propeller shaft, submergence depth of the shaft, rotational speed of the propeller and the design features of the propeller. Keeping in view the above points, the present investigation was focussed on determining the effect of various geometric and dynamic conditions on aeration efficiency of a propeller-aspirator-pump aerator.

2. Theoretical Considerations

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The standard oxygen transfer rate (SOTR) of an aerating device is defined as the mass of oxygen that the device can introduce into a body of water per unit time at standard conditions (20°C water temperature, 0 mg/l initial DO concentration, one atmospheric pressure and clear tap water [2].

$$SOTR = K_La_{20} \times (C^* - C0) \times V = K_La_{20} \times 9.07 \times V \times 10^{-3} \quad (1)$$

where, SOTR = standard oxygen transfer rate (kg O_2/h), k_La_{20} = overall oxygen transfer coefficient at 20°C (h^{-1}) = k_La_T/θ^{T-20}, k_La_T = overall oxygen transfer coefficient at T°C (h^{-1}), θ = temperature correction factor = 1.024 for pure water, C* = saturation value of DO at test conditions (mg/L), C0 = DO concentration at time t = 0 (mg/L), 9.07 = saturation value of DO (mg/L) at 20°C and one atmospheric pressure and V = aeration tank volume (m3). It is an important parameter used to compare aerators. A better comparative parameter is the standard aeration efficiency (SAE), which is defined as the SOTR per unit of power [3].

$$SAE\ (kg\ O_2/kWh) = SOTR\ (kg\ O_2/kWh) / P \quad (2)$$

2.1. Dimensional analysis

The basic dimensional analysis of aeration process has been presented by many investigators [4], [5], [6], [7], [8], [9]. The main parameter of the absorption process is the absorption rate coefficient kLa20× V, can be expressed as [7].

$$K_La_{20} \times V = SOTR / \Delta C \quad (3)$$

Where, ΔC = DO deficit = C* - C0

The functional relationship between SOTR/Δc and the variables may be expressed as: ν

$$SOTR / \Delta C = f1\ (\alpha, d, V, N, g, \rho a, \rho w, \nu_w, \sigma_w) \quad (4)$$

where α = positional angle of propeller shaft; d = submergence depth of propeller shaft i.e., the distance between the water surface and the water suction hole; V = volume of water in the tank; N = Rotational speed of propeller; g = acceleration due to gravity; ρ_a = mass density of air; ρ_w = mass density of water; ν_w = kinematic viscosity of water and σ_w = surface tension of water.

Based on Buckingham Π theorem, Eq. (4) may be expressed as follows:

$$Y = f_2\ \{\alpha, V/d^3, N^2d/g, \rho_a/\rho_w, Nd^2/\nu_w, \sigma_w/(g\rho_w d^2)\} \quad (5)$$

where, Y = absorption number = $SOTR \times (\nu / g^2)^{1/3} / (\Delta C \times d^3)$, N^2d/g = Froude number (Fr), Nd^2/ν_w = Reynolds number (Re) and $\sigma_w / (g\rho_w d^2)$ = Weber number (W). As the aeration tests were performed on a practically identical system (pure water-air), ρ_a/ρ_w and W remain constant in the aeration tank and subsequently can be omitted from Eq. 5.

Aerator power to water volume ratio should be less than 0.1 kW/m^3 [10]. Thus in the present study, based on the power consumption of the propeller, water volume was chosen to satisfy the above condition. Hence, the term V/d^3 is also omitted from Eq. (5). Thus, simplification of Eq. (5) results in

$$Y = f_3\ [\alpha, Fr, Re] \quad (6)$$

The power consumption P of a given propeller-aspirator pump aerator is, in general, dependent upon the same parameters as the term SOTR/ΔC. In a similar way, with the help of dimensional analysis the following relationship for power consumption, P is obtained:

$$Ne = f_4\ [\alpha, Fr, Re] \quad (7)$$

$$\text{Where, } Ne = \text{power No} = P / (\rho_w \times N^3 \times d^5) \quad (8)$$

SAE was also expressed in a non-dimensional form (E) by dividing the absorption number (Y) with power number (Ne) as follows: [8], [9].

$$E = Y/ Ne = (SOTR / P) \times (\nu_w / g^2)^{1/3} \times (\Delta C \times d^3)^{-1} \times \rho_w \times N^3 \times d^5$$

$$\text{or, } E = SAE \times (\nu_w/g^2)^{1/3} \times (\Delta C)^{-1} \times \rho_w \times N^3 \times d^2 \quad (9)$$

$$\text{or, } E = f_5\ [\alpha, Fr, Re] \quad (10)$$

3. Materials and Methods

3.1. Aeration test

The aeration experiments were conducted in a brick masonry tank of dimension 5 × 3 × 1.5 m^3. The positional angle of propeller shaft α (inclination of the shaft with the horizontal water surface) can be changed by changing the position of an arm attached to the supporting structure. The atmospheric air enters through the hole A of the propeller shaft due to suction created by the aspirator. Water drawn through the hole B is thoroughly mixed with the air and is finally splashed into the atmosphere. Initially the tap water was deoxygenated using 0.1 mg/L of cobalt chloride and 10 mg/L of sodium sulphite for each 1 mg/L of dissolved oxygen present in water [11]. Thereafter the aerator was operated at the desired conditions as per the experimental design and readings were taken at timed intervals till DO increased from zero to about 80% saturation. The DO deficit was computed for each time. Finally the values of SOTR and SAE were calculated using Eq. 1 and 2 respectively.

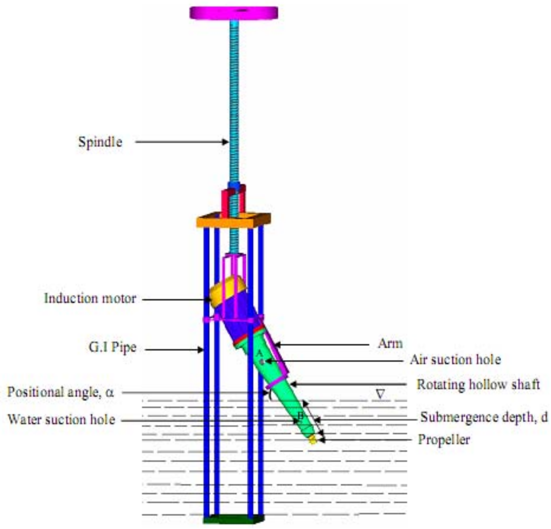

Fig.1. Experimental setup for testing of propeller-aspirator-pump aerator.

3.2. Experimental design

3.2.1 Effect of positional angle of propeller shaft on oxygen transfer

To obtain the optimum value of α, aeration tests were conducted on propeller-aspirator pump aerator positioned at five different positional angles (α): 90°, 75°, 60°, 45° and 30° keeping the dynamic conditions (rotational speed of the shaft, N and submergence depth of the propeller, d) constants. The rotational speed of the shaft (N) and submergence depth of the propeller (d) were fixed at 2130 rpm and 300 mm respectively. In each case, the volume of water to be aerated (V) was maintained to satisfy: $P/V \leq 0.1$ kW/m^3 [10].

3.2.2 Effect of dynamic conditions (Fr and Re) on oxygen transfer and power consumption

Keeping the optimized value of α (obtained from previous set of experiments) constant, N and d were varied simultaneously to find out the effect of different dynamic conditions on E and Ne. The ranges of variation of N and d were from 1420 to 2840 rpm (at an interval of 355 rpm) and 140 to 460 mm (at an interval of 80 mm) respectively amounting to 25 sets of experiments.

4. Results and Discussion

4.1. Determination of optimum positional angle (α) of propeller shaft

Aeration tests were conducted using different values of α. A typical plot showing the variation of E with α is shown in Fig. 2. It is seen from the figure that all the points could be well fitted by a second order polynomial equation with the variation of α in the range of 30 to 90°.

$$E = - 4 \times 10\text{-}6 \times \alpha^2 + 0.0006 \times \alpha - 0.0017 \quad (11)$$

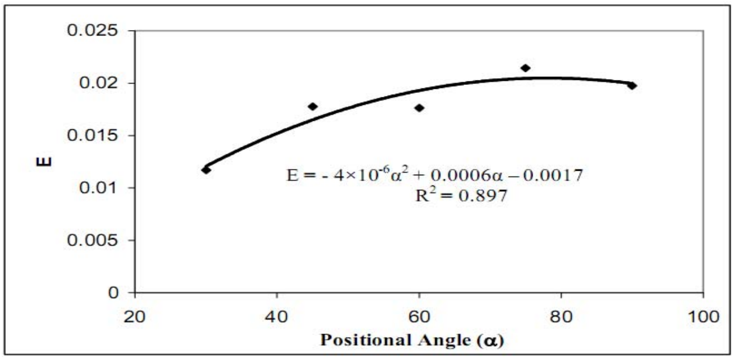

Fig.2. Variation of E with positional angle of propeller shaft.

From the developed relationship, the value of α, at which E reaches the peak value, is found to be 75°. In this case, E is directly proportional to SAE as N and d were kept as constants. Hence the optimum positional angle corresponds to maximum SAE also.

4.2. Effect of dynamic conditions (Fr and Re) on oxygen transfer and power consumption

4.2.1 Effect of Re and Fr on E

The relationship between E and Fr is shown in Fig.3. It can be seen from Figure that the data points for different submergence depths are close to each other and could be well fitted by the following equation:

$$E = -0.0002 \times Fr^2 + 0.876 \times Fr / [5.28 + 0.0068 \times Fr + (3310/Fr)] \qquad (R^2 = 0.976) \qquad (12)$$

However, no unique relationship could be established between Re and E.

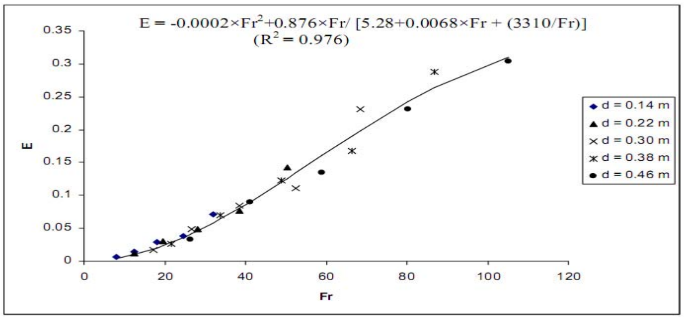

Fig.3. Effects of Froude criterion on E.

4.2.2 Effect of Re and Fr on Ne

The relationship between Ne and Re is shown in Fig.4. It can be seen from Figure that the data points for different submergence depths are close to each other and could be well fitted by the following equation:

$$Ne = 11.139 \times (10^{-5}\ Re)^{-2.3213} \qquad (R^2 = 0.944) \qquad (13)$$

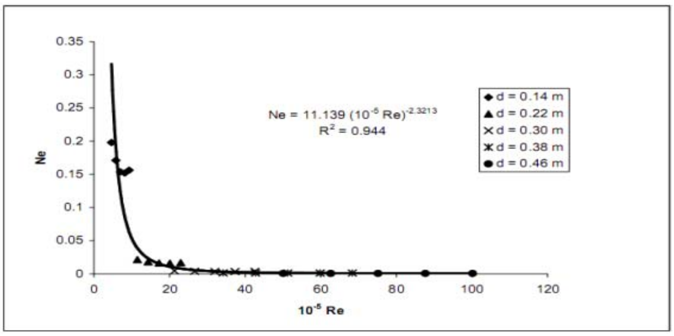

Fig. 4 Effects of Reynolds criterion on Ne.

However, no unique relationship could be established between Fr and Ne

4.3. Optimum dynamic condition for propeller-aspirator-pump aerator

To arrive at a particular dynamic condition that yields the maximum SAE, E was expressed in terms of SAE (Eq. 9) assuming the water temperature to be 20°C, value of g as 9.81 m/s^2, ΔC as 9.07 mg/L, ρ_w as 1000 kg/m^3, equated to Eq. (12) and the following expression is obtained:

$$SAE = [0.0002 \times Fr^2 + 0.876 \times Fr / [5.28 + 0.0068 \times Fr + (3310/Fr)] / (240.59 \times N^3 \times d^3) \qquad (14)$$

The above equation is valid subject to $7.993 \le Fr \le 105.057$. Substituting $Fr = N^2 d/g$ in the above equation, an unconstrained nonlinear programming was followed using WinQSB (version 1.00) to determine the values of N and d at which SAE is maximum.

The maximum value of SAE was found to be 0.42 kg O_2/kW h at a submergence depth of propeller shaft, d = 0.14 m and rotational speed of N = 2837.59 ≈ 2840 rpm. To calculate the power consumption, Eq. (13) can be rewritten by substituting $Ne = P/(\rho_w N^3 d^5)$, $Re = Nd^2/\nu_w$ (assuming water temperature = 20°C), ρ_w = 1000 kg/m^3, N = 2840/60 = 47.33 rps, d = 0.14 m and $\nu_w = 1 \times 10^{-6} m^2/s$ as shown below.

$P = 11.139 \times \rho_w N^3 d^5 \times (10^{-5} Nd^2/\nu_w)^{-2.3213}$

$= 11.139 \times 1000 \times 47.333 \times 0.14\ 5 \times [10^{-5} \times 47.33 \times 0.142/(1 \times 10^{-6})]^{-2.3213}$

= 360.8174 W = 0.361kW

Thus, SOTR = SAE × P = 0.42 × 0.361 = 0.15 kg O_2 /h

Therefore, a maximum SAE of 0.42 kg O_2/kW h and corresponding SOTR of 0.15 kg O_2/h can be obtained by operating the propeller-aspirator-pump aerator at a submergence depth, d = 0.14 m and rotational speed, N = 2840 rpm.

5. Conclusions

Experiments were conducted at different dynamic conditions keeping the geometric condition constant (α = 75°). The results showed that E and Ne are well correlated with Fr and Re respectively. Maximum SOTR and SAE are found to be 0.15 kg O_2/h and 0.42 kg O_2/kW.h respectively at rotational speed (N) of 2840 rpm, submergence depth (d) of 0.14 m and positional angle of 75° of the propeller shaft.

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